NEXT GENERATION ROBUST LOW NOISE SEISMOMETER FOR NUCLEAR MONITORING

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PMD Scientific, Inc.

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ABSTRACT

Effective global monitoring of nuclear explosions calls for a worldwide network of seismic stations equipped with the next generation high quality digital seismometers for nuclear monitoring recording data in the 0.02–16Hz band. This project addresses these requirements: it is aimed at the implementation of the next generation, very low noise, broadband, wide dynamic range, extremely robust force-balanced digital seismometer for seismic monitoring of nuclear explosions. Successful completion of this project will serve vital national interests in greatly facilitating global compliance with nuclear non-proliferation and detection of possible violations of the Comprehensive Nuclear-Test-Ban Treaty by rogue states. The new seismometers should also be very competitive in various niches of the worldwide seismic market due to their valuable combination of high performance and exceptional ruggedness. The new generation seismometer uses improved electrochemical transducers built into three similar orthogonally mounted sensors, the latter based on conceptually new design ideas that, when implemented, will result in a drastic increase in signal to noise ratio. The principles of operation and detailed noise analysis of electrochemical motion sensors are presented along with the explanation of how such major noise reduction can and will be achieved. The new concept has shown to be promising based on test results of the experimental sensor prototypes. The new instruments should be easily and quickly deployable in field and stationary vault environments; they will be highly reliable and offer low cost of ownership since they require no maintenance: no mass locks; no mass position monitoring and/or mass centering over the full temperature range of -12 to +60C. The extremely rugged design will greatly reduce the probability of damaging such instruments during transportation and handling. The seismometer will incorporate a high-resolution, low-noise, very low power versatile 24-bit digitizer that will provide digital outputs with velocity-flat and optional acceleration flat and combined velocity/acceleration-flat response. The noise level of the proposed seismometers will be below the United States Geological Survey (USGS) New Low Earth Noise Model with the dynamic range of no less than 136dB over the 0.02 to the 16Hz frequency band. Maintaining the wide dynamic range, the uniform frequency response over the passband, and the considerably reduced noise will be greatly facilitated by the use of the efficient force-balancing electrodynamic feedback. In addition to the digitizer, each seismometer will also contain an ultra-low power microcontroller that will monitor gain and transfer function stability, provide for prompt, accurate temperature compensation over the full operating temperature range and perform on demand or periodical seismometer calibration. The complete digital seismometer is expected to consume less than 750mW.

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OBJECTIVES

Our current electrochemical sensors partially satisfy and all but one of the desired characteristics: their noise is at -170dB in the 0.05–8Hz band and thus has to be lowered by 15-20dB to be ~10dB below the NLNM in the broader (0.02 – 16Hz) band. Therefore, a radically new concept is needed that would lead to such significant noise reduction without sacrificing any of the original advantages of electrochemical sensors.

The ultimate objective of this project was to demonstrate the feasibility of the development of a novel force-balanced electrochemical seismic sensor with noise of at least 10dB below the USGS NLNM. Proof-of-concept prototype digital seismometers will be built and tested side-by-side with reference STS2 instruments.

Objective: **Seismometer Noise.** Achieve the target noise levels shown in the Table below. Also included are the numbers anticipated to be achieved in the Phase II project:

Passband	Target Noise Levels	
	Phase I	Phase II
0.02-0.1Hz	-178 to -185dB♦	-185 to -190dB♦
0.1 – 6Hz	-180 to -185dB*	--185 to -190dB*
6 – 16Hz	-180 to -170dB•	(-185 -190) to -180dB•

Notes: ♦ slightly bending upward toward longer periods; * practically flat; • sharper break toward higher frequencies similar to that observed in traditional seismometers.

Objective: **Dynamic Range >136dB.** Demonstrate that implementation of the new design concept will not affect the instrument’s dynamic range (our current production BB603 seismometers have a dynamic range of ~150dB).

Objective: **Robustness.** Demonstrate that the targeted noise reduction will not require sacrificing of the inherent robustness of the electrochemical sensors. No mass locking mechanism should be used. Since electrochemical seismic sensors do not contain delicate moving mechanical parts they are extremely rugged. The newly proposed sensor promise to be even more rugged since it will have much smaller external inertial mass.

Objective: **No Maintenance operation.** Demonstrate that the two signature features of electrochemical seismometers: no mass position monitoring/centering and ability to work with significant installation tilts will be preserved; the second feature is especially important for the borehole sensors.

Objective: **Passband & Response.** Velocity-flat response in the required 0.02 – 16Hz band. The passband will be defined by the -3 dB corner frequencies with the ripple in gain of no more than +/- 1 dB from the mean gain values as measured from one octave above the lower corner frequency to one octave below the upper corner frequency

Objective: **Digital Seismometer Power Consumption:** <750MW at 12Vdc. Of that amount the anticipated digitizer’s share will be about two thirds.

RESEARCH ACCOMPLISHED

ELECTROCHEMICAL TRANSDUCER BASICS

A typical sensor (Figure 1) has a plastic housing filled with strong electrolytic solution: potassium iodide, *KI*, with a small addition of iodine, I_2. Electrolyte is contained between a pair of elastic membranes that significantly contribute to the sensor's transfer function. The transducer consists of four fine platinum mesh electrodes, two anodes, and two cathodes, separated by thin polymer mesh or laser-perforated mica spacers. The stack is tightly held together between two flanges. The motion of the fluid caused by an external acceleration is converted into an electrical signal via convective diffusion of the ions in the electrolyte. When a small dc offset is applied between the anodes and cathodes, the flow of ions of each type can be described by the following expression (Newman, 1973; Koryta and Dvorak, 1993).

$$\mathbf{j}_a = -D \cdot \nabla c_a + q_a \cdot c_a \cdot \mu \cdot \mathbf{E} \tag{1}$$

Where D = diffusion coefficient; μ = mobility and c_a = concentration of active ions; **E** = the electrical field vector. Since the strong electrolyte is an excellent conductor, the electric potential drops rapidly in the vicinity of the electrodes, and there is no electric field in the bulk of the fluid. Thus the second term in Equation 1 can therefore be ignored. Therefore, the application of a bias voltage results *only* in a concentration gradient. An acceleration, **a,** along the channel creates a pressure differential, **ΔP,** across the transducer, which forces the liquid to move with a velocity, **v**. This flow of electrolyte entrains ions and causes an additional charge transfer between the electrodes:

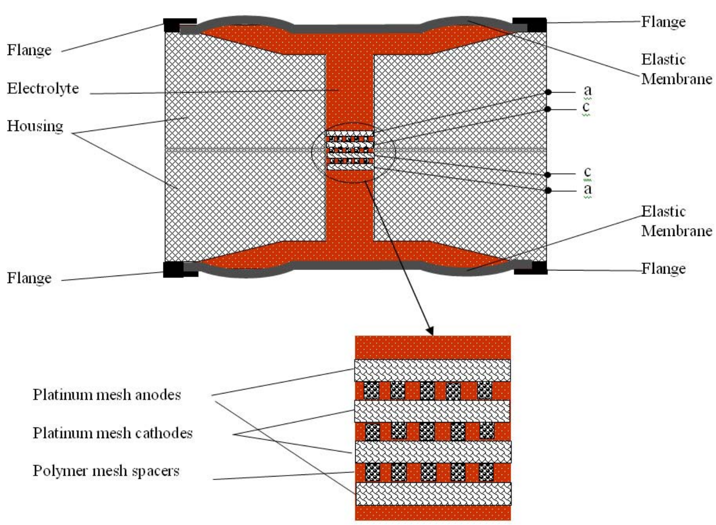

Figure 1: Basic Electrochemical Seismic Sensor.

$$\mathbf{j}'_\mathbf{a} = \mathbf{v} \cdot c_a \tag{2}$$

The total current from active ions, in the presence of acceleration, can be expressed as:

$$\mathbf{j}_\mathbf{a} = -D \cdot \nabla c_a + \mathbf{v} \cdot c_a \tag{3}$$

Thus the transducer generates an electrical signal in response to acceleration.

A general expression describing noise in units of external acceleration:

$$\left\langle a^2 \right\rangle_\omega = \frac{2R_h kT}{(\rho L)^2} \tag{4}$$

Where: ρ = electrolyte density; L = electrolyte effective length in the direction of the acceleration; k = Boltzmann constant; T = absolute temperature; R_h = hydraulic impedance. The nominator in Equation 4 represents hydrodynamic thermal noise, similar to the Nyquist noise in electric circuits with the R_h standing for the electric resistance R (Van der Ziel, 1970). The total noise of a sensor agrees with Equation 4 only in the mid-frequency region. The elevated noise spectral density at both ends of the passband is due to at least two addition sources. The additional noise is unavoidable even when the two halves of the transducer are exactly symmetrical and thus their noise components add up to zero at the transducer differential output. These two sources are: fluctuation noise of the current flowing in the transducer; noise of the electronic amplifiers

The spectral density of fluctuation noise is described by the general equation:

$$\left\langle I^2 \right\rangle_\omega = 2qI \tag{5}$$

Where I = quiescent current of the transducer cell (Abramocvich and Daragan, 1992-94):

$$I = \frac{Dc_0 eS}{l}\left(1 - \exp(-\frac{qU_0}{kT})\right) \tag{6}$$

q = elementary charge in the cell. As two electrons participate in each elementary charge exchange reaction at the electrodes, $q = 2e$; D = diffusion coefficient; c_0 = charge carriers equilibrium volumetric concentration; U_0 – voltage between and S = effective area of the electrodes; l = distance between the electrodes. Since each transducer consists of two independently working identical cells that are together characterized by the transfer function W, the following equation describes sensor fluctuation noise in units of acceleration:

$$\left\langle a^2 \right\rangle_\omega = 8eI \big/ (W/\omega)^2 \tag{7}$$

The practical method of increasing the signal-to-noise ratio is an addition of an inertial mass. For example, vertical and horizontal sensors of the PMD BB603 broadband seismometer are equipped with ~650g masses which results in noise below NLNM in the 0.06 – 8Hz. To account for the additional mass Equation 4 is modified:

$$\left\langle a^2 \right\rangle_\omega = \frac{2R_h kT}{(\rho L + M/S_s)^2} \tag{8}$$

Where M = external mass and S_s = effective area of the sensor membrane. This is a simple, proven approach; it is easy to change/adjust M; the additional mass ("frame") is mounted in such a way that the membranes are not deformed. The frame carries a voice coil that transmits the feedback force to the membrane. Both qualitative and quantitative validity of Eq.10 have been confirmed experimentally. Evidently, further increase of the inertial mass would be impractical.

PROPOSED DEVICE CONCEPT

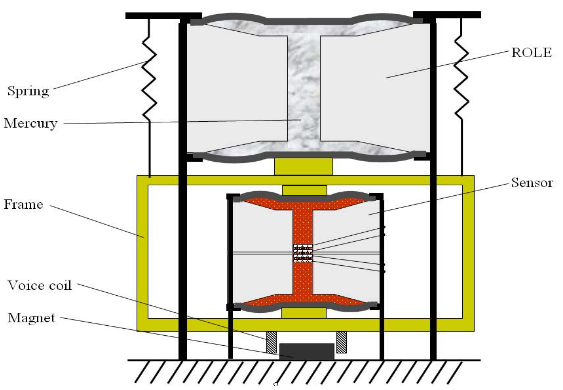

Figure 2: HEX design concept.

To achieve the required noise levels a radically new approach is necessary. While there is no known electrolyte with much higher density, a well known exceptionally heavy liquid exists: ***mercury*** (13.6 g/cm^3). The conceptual design of a sensor that we called Hybrid Electro-Chemical Sensor (HEX) is shown in Figure 2. A smaller electrochemical sensor has a frame with a voice coil moving around a magnet working in the force-balancing loop. The frame's top is firmly tied to the lower membrane of a larger sensor-like structure filled with mercury. The frame in such structure performs several functions: it carries the voice coil and thus transfers the balancing force to the sensor; it transfers pressure from the upper to the lower device; finally, it is attached to the suspension springs that balance the weight of the total oscillatory mass consisting of the frame itself, mercury and electrolyte. An external acceleration along the sensitive axis is transformed into pressure differential, ΔP_i, between membranes in each of the two pairs: the large upper and the small lower. The following equation describes HEX noise:

$$\left\langle a^2 \right\rangle_\omega = \frac{2R_h kT}{\left(\rho_m h_m \dfrac{S_m}{S_s}\right)^2} \tag{9}$$

Where ρ_m and h_m are respectively density and column height of mercury and S_m = area of the ROLE membrane (we called the mercury-filled device 'ROLE' – short for '**ρ-L-E**nhancer': see ρ, L terms in Equation 4).

Comparison of Equations 4 and 9 shows that the new concept not only capitalizes on the very high density of mercury, but achieves more than that: since the noise is inversely proportional to the ratio of the diameters of the two membranes it is possible to achieve an even larger increase in signal-to-noise ratio.

During Phase I research numerous vertical HEX sensors were built and tested. Initial tests were performed at PMD facility. A BB603 instrument specially tuned for the 0.02 – 16Hz band and with inertial mass increased to ~1.3kg was used as a reference. Most tests involved this reference and a pair of experimental sensors all placed on the same granite plate. The use of three instruments was necessitated by PMD noise calculation algorithm; all calculations were performed using DADiSP spreadsheet package. Many different configurations of HEX sensors were tested with various degrees of success. We encountered several unexpected phenomena. First off, our smallest diameter membrane that was promising the greatest gain in signal to noise ratio proved to be mechanically unstable. Several changes to the mold somehow improved its performance, however strong signals usually resulted in parasitic spikes. The strict time limits of the Phase I research did not allow us to manufacture another mold. Thus we had to make do with the larger size sensor membranes and therefore a limited S_m / S_s ratio.

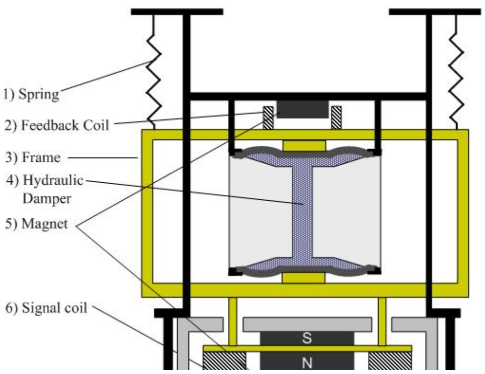

Figure 3. Electrodynamic reference sensor with hydraulic Damper.

Being understandably forced to test the preliminary prototypes at the PMD facility, we had to take into account the local background seismic noise. The area is mostly industrial, thus nightly and especially weekend nightly traffic is very scarce although a major street runs about ¾ miles away. PMD occupies a central part of a long, single storey industrial building. In a windless weekend night the long period noise in the passband of interest is at or slightly below -170db. The noise above several Hertz is always significant here though we could not tell whether it should be attributed more to the natural local background noise or to the noise of our instruments, whichever is higher. In order to find out the answer we built a special test instrument with inherently low noise at higher frequencies. An obvious and relatively simple solution would be using an electrodynamic transducer since its yield increases with frequency. At the same time we wanted this test instrument to share as much as possible its mechanical characteristics with an electrochemical sensor. A sketch of this force-balanced electrodynamic sensor is shown in Figure 2.

The inertial mass (frame, 3) is suspended on two springs, 1, and attached to the centers of the two membranes, similar to those used in standard electrochemical sensors. By measuring the time it takes for a known volume column of water to flow through a transducer, we determined experimentally the required diameter of the channel in the hydraulic damper, 4. The feedback coil, 2, is glued to the upper bar of the frame; the lower bar carries the pick-up coil, 6, which envelopes two very strong rare-earth magnets, 5.

To analyze the operation of such a hydraulically damped system let us start with the well-known generic equation of seismometer,

$$m \cdot \ddot{x} + D \cdot \dot{x} + K \cdot x = m \cdot \ddot{w} \qquad (10)$$

where: $\boldsymbol{m}$ = inertial mass; $\boldsymbol{x}$ = displacement of the inertial mass relative to the seismometer body; $\boldsymbol{w}$ = ground motion; $\boldsymbol{D}$ = damping coefficient; $\boldsymbol{K}$ = rigidity of the suspension.

In case of hydraulic damping this equation takes a slightly different form:

$$m \cdot \ddot{x} + K_s \cdot x + F_m = m \cdot \ddot{w} \qquad (11)$$

Where: $\boldsymbol{K_s}$ = rigidity (rate) of the suspension spring, and $\boldsymbol{F_m}$= the restoring force generated by the membranes. This force depends not only on the displacement $\boldsymbol{x}$ but also on the volume of the liquid in the buffer space under each membrane. This volume determines the initial position, $\boldsymbol{x_0}$, of the membrane. Assuming small displacements, this force can be expressed as

$$F_m = 2K_m (x - x_0) \qquad (12)$$

where $\boldsymbol{K_m}$ = rigidity (rate) of each membrane. Also,

$$\Delta x_0 = \frac{\Delta V}{S_m} \tag{13}$$

where: ***V***=volume of the liquid in the buffer space and $\boldsymbol{S_m}$= effective area of the membrane. Now we can rewrite equation 8 in the following manner:

$$m \cdot \ddot{x} + K_s \cdot x + 2K_m \left(x - x_0\right) = m \cdot \ddot{w}\,. \tag{14}$$

In turn, $\boldsymbol{x_0}$ is related to the displacement of the inertial mass:

$$\frac{dx_0}{dt} = \frac{dV}{dt} \cdot \frac{1}{S_m} = \frac{P}{R_h \cdot S_m} = \frac{K_m}{R_h \cdot S_m^2}\left(x - x_0\right) \tag{15}$$

Where: P = pressure of the liquid and R_h= hydraulic impedance of the damper channel. For the sake of convenience we will rewrite equations 11 and 12 using Laplace operator ***s*** that for harmonic signals equals $\boldsymbol{j\omega}$:

$$m \cdot s^2 x + K_s x + 2K_m \left(x - x_0\right) = m \cdot s^2 w \tag{16}$$

$$s \cdot x_0 = \frac{K_m}{R_h \cdot S_m^2}\left(x - x_0\right), \text{ and thus} \tag{17}$$

$$x_0 = x \cdot \frac{K_m}{R_h \cdot S_m^2 \left(s + \dfrac{K_m}{R_h \cdot S_m^2} \right)}\;. \tag{18}$$

And after substituting $\boldsymbol{x_0}$ from equation 17 into equation 15,

$$x \cdot \left(m \cdot s^2 + K_s + \Gamma\right) = m \cdot s^2 w \tag{19}$$

Where: $\Gamma = 2K_m \left(\dfrac{s}{s + \dfrac{K_m}{R_h \cdot S_m^2}} \right)$. Looking at the expression in the parentheses, it is easy to conclude that at low frequencies, when $\boldsymbol{\omega}$ is small, $\boldsymbol{\Gamma}$ is reduced to $\boldsymbol{2R_h \cdot S_m^2 \cdot s}$, and represents the damping factor. At higher frequencies, the $K_m / R_h \cdot S_m^2$ term becomes much smaller than ***s***; $\boldsymbol{\Gamma}$ reduces to $\boldsymbol{2K_m}$, there is no additional damping in the system and the rigidities of the suspension spring and the membranes are added together.

Optimization of the damping is tightly connected with several additional critical parameters of the hydraulic device, in particular its possible contribution to the sensor noise.This hydraulic device plays several important roles in the system aside from the above described damping action. Indeed, the whole sensor is built around it: the inertial mass is suspended on its membranes; both pickup and feedback coils are mounted, in turn, on the inertial mass; the membranes provide proper centering of the whole oscillating system. The magnetic circuits are mounted on the damper assembly. Finally, it acts as an effective shock absorber during handling, transportation, and operation of the seismometer.

As mentioned above, the transducer directly measures the velocity of motion of the pickup coil relatively to the magnet that is attached to the seismometer base. Using Equation 16, one can find the relation between ground motion and this velocity:

$$x = \frac{m \cdot s^2 \cdot w}{m \cdot s^2 + K_s + \Gamma} \tag{20}$$

In the very low-frequency band (below 01Hz) this expression reduces to:

$$x = \frac{m \cdot s^2 \cdot w}{K_s + 2R_h \cdot S_m^2 \cdot s} \tag{21}$$

Evidently, $s^2 \cdot w$ is ground motion acceleration. Then the corresponding pickup coil velocity, V_c, when s is so small that the second term in the denominator in Equation 12 can be neglected, will be expressed as follows:

$$V_c = s \cdot x \approx \frac{m}{K_s} \cdot s^3 \cdot w = \frac{m}{K_s} \cdot s \cdot a_{gnd} \tag{22}$$

where a_{gnd} = ground motion acceleration. Therefore, as expected, the pickup signal will be proportional to the ground motion frequency and inversely proportional to the rigidity of the suspension. The latter is a sum of the rates of suspension springs and membranes.

This sensor with inertial mass about 1.3kg performed rather well and indicated that during very quiet nights the background noise level at frequencies of several Hertz and higher was slightly below that of the HEX sensor. This result was rather surprising since, according to all calculations and general considerations, HEX sensor should have had a much lower noise at these frequencies. One of the contributors to this noise turned out to be a resonance peak at about 15–20Hz that had to be suppressed electronically. Other factors that will have to be investigated experimentally in Phase II will be combined noise from four membranes and hydraulic noise from the mercury-filled ROLE device. Evidently, we will have to optimize both geometries.

In March, 2008, we brought the best prototype HEX and the reference electrodynamic sensor to Albuquerque Seismological Laboratory (ASL) in Albuquerque for side-by-side testing against a high-gain STS2 seismometer. The recording was performed on Quanterra Q330 with two sampling rates: 1sps and 100sps. We selected a seemingly quietest period for noise evaluation using a PMD-developed algorithm based on data from three instruments. A superposition of three instrument-generated 1sps traces after correction for transfer function is shown in Figure 4 and noise curves calculated based on 100sps recordings in Figure 5.

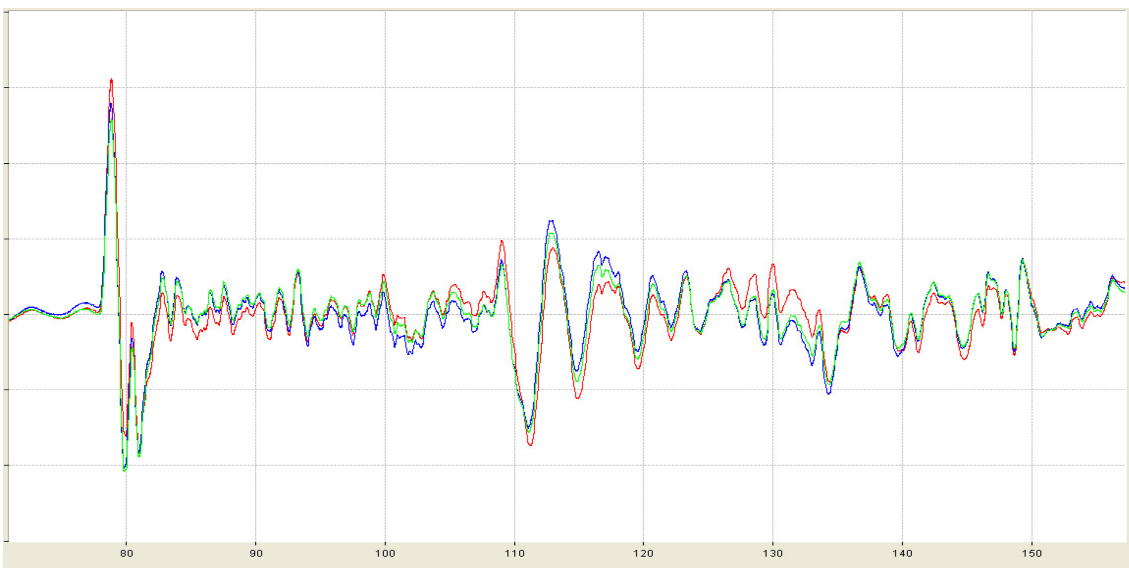

Figure 4. Red-STS2; Blue – electrodynamic sensor, green – HEX sensor recorded at 1sps.

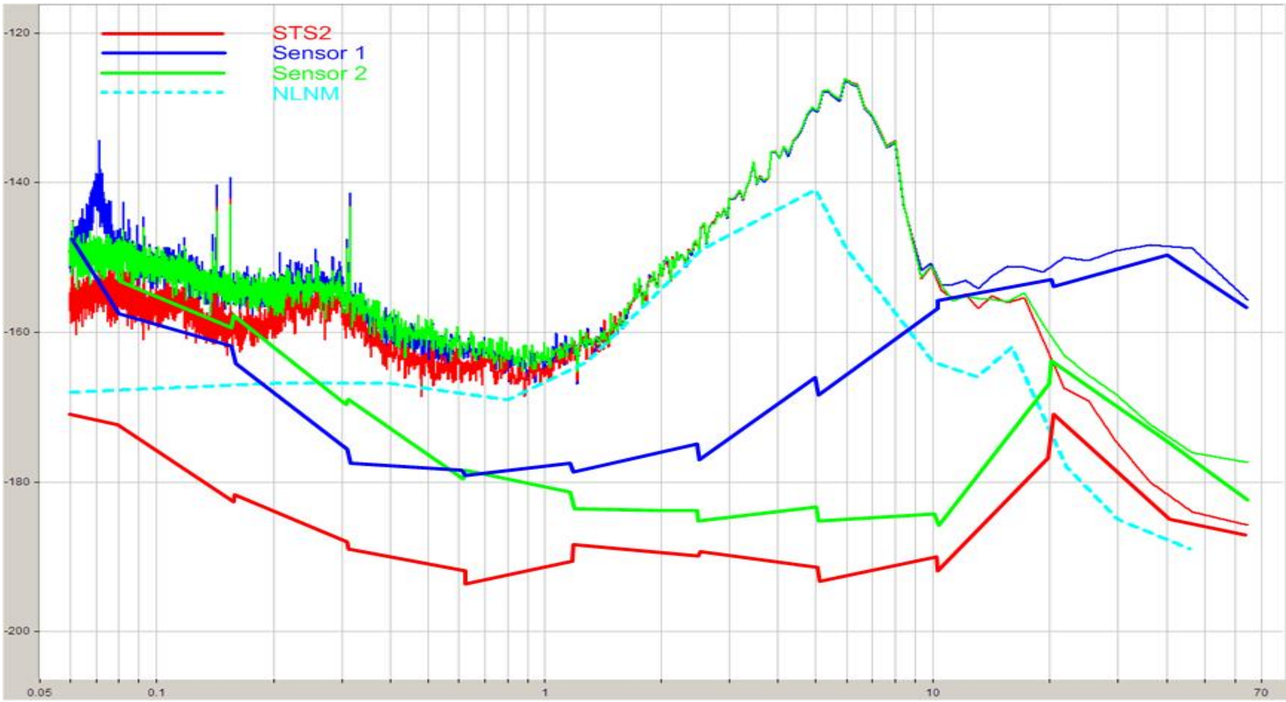

Figure 5. Noise curves. Sensor 1 – electrodynamic; sensor 2 – HEX.

Phase I objectives called for the following noise levels.

In the 0.02 to 0.1Hz passband noise curve was expected to go down from approximately -178dB to -185dB;
In the 0.1 to 6Hz band, the curve was expected to stay more or less flat within -180– -185dB margins;
Finally, from 6 to 16Hz the curve was expected to go up to approximately -170dB.

The prototype HEX sensor behaved in a way that we did not fully anticipate. Indeed, in the long period region, where we expected to encounter the most difficulties, the noise stayed below -180dB to between 1 to 20sec. The higher frequency noise went up from about 1sec. The seemingly sharp noise increase of both the HEX sensor and STS2 from 10s to longer periods should be explained by the imperfection of our noise cross-correlation calculation program: when one of the three sensors (in this case the electrodynamic sensor) has a significantly higher noise it obviously "pulls" with it two other test sensors, in this case the HEX and STS2. Therefore, the persistent ~6db differential between the STS2 and HEX after 10s may indicate that the latter indeed had a pretty low noise in this region, possibly to the desired levels.

The unexpected rise of the noise starting from about 1Hz and up can be partially explained by the smaller than intended S_m/S_s ratio. Also this should suggest flaws in our mathematical model since the latter does not show noticeable frequency dependencies in the passband of interest. Had we been able to use the 25-mm-diameter sensor membrane, the whole curve would have shifted down by 6 to 10dB. But even in this case noise at 6Hz would be approximately -173 – -175dB or 7 to 10dB higher than desired. Fortunately, this mystery turned out to be easy to solve simply by looking at the noise curve of the electrodynamic sensor. The latter was supposed to have exceptionally low noise at higher frequencies and though it demonstrated a much better noise then HEX, starting at about 1Hz and up, the absolute noise levels were highly disappointing. We discovered the problem that was common for both test sensors on our return to PMD. All attention was paid to improving the transducers signal yield. Almost at the last moment it was decided to further enhance the low-frequency response of the test sensors by reducing their natural frequencies. Thus, we quickly designed and built astatizing suspensions, somehow similar to the original LaCost configuration. However, we evidently did not take into account the presence of another flexible member of the overall design: the membrane. When a signal is applied to the calibration input, it is easy to observe warping of the upper membrane (the one connected to the suspension system). Such warping is more detrimental at higher frequencies where, in particular, it results in several minor resonances that undoubtedly contribute to the

elevated noise. When we later replaced the "improved" suspension with a straight spring, the membrane moved along the direction of the axis of sensitivity without any noticeable parasitic warping. In addition, LaCost astatizing requires zero-length springs that we did not have in our possession.

CONCLUSIONS AND RECOMMENDATIONS

Test results of the prototypes built during the Phase I effort, have proven the feasibility of the concept and of the proposed seismometer. A prototype instrument with noticeably reduced noise in comparison with the presently manufactured electrochemical seismometers exhibits the same ruggedness/robustness, passband, no maintenance operation (i.e., it does not require mass positioning and probably will not require the use of mass locks). Analysis of the field test results clearly points out the first step of the necessary improvements. At the exceptionally low noise levels required there is no doubt that several iterations of improvements and corrections will be needed. The most valuable lesson learned from the first experiments: do not do anything without very thorough evaluation no matter how "obvious" the results could be.

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REFERENCES

Newman L. (1973). *Electrochemical Systems*, Prentice-Hall, Englewood Cliffs, NJ.

Koryta L and K. Dvorak (1993). *Principles of Electrochemistry*, J. Wiley, New York.

Van der Ziel A. (1970). *Noise; sources, characterization, measurement*, Prentice Hall.

Abramovich I. and S. Daragan, 1992–1994). *New Family of Inexpensive Broad Band Seismometers*, NSF SBIR Grant No. III-9360412.